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LETTERS

# Predecessors of the giant 1960 Chile earthquake

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**It is commonly thought that the longer the time since last earthquake, the larger the next earthquake's slip will be. But this logical predictor of earthquake size[1], unsuccessful for large earthquakes on a strike-slip fault[2], fails also with the giant 1960 Chile earthquake of magnitude 9.5 (ref. 3). Although the time since the preceding earthquake spanned 123 years (refs 4, 5), the estimated slip in 1960, which occurred on a fault between the Nazca and South American tectonic plates, equalled 250–350 years' worth of the plate motion[3,6–10]. Thus the average interval between such giant earthquakes on this fault should span several centuries[3,9,10]. Here we present evidence that such long intervals were indeed typical of the last two millennia. We use buried soils and sand layers as records of tectonic subsidence and tsunami inundation at an estuary midway along the 1960 rupture. In these records, the 1960 earthquake ended a recurrence interval that had begun almost four centuries before, with an earthquake documented by Spanish conquistadors in 1575. Two later earthquakes, in 1737 and 1837, produced little if any subsidence or tsunami at the estuary and they therefore probably left the fault partly loaded with accumulated plate motion that the 1960 earthquake then expended.**

The 1960 Chile mainshock resulted from a rupture nearly 1,000 km long on a north–south trending fault that conveys the subducting Nazca plate beneath South America at rates averaging 8 m per century[3]. Lurching westward above the rupture, the South America plate rose in a mostly offshore area while subsiding 1–2 m in a coastal downwarp[6] (Fig. 1b). The ensuing tsunami, with crests 10–15 m high in Chile[11], reached maximum heights of 10 m in Hawaii[12] and 6 m in Japan[13].

The 1960 earthquake was preceded historically by earthquakes in 1575, 1737 and 1837 (Fig. 1b; Supplementary Table S1). The reported effects from 1575 most nearly resemble those from 1960 (ref. 4). Conquistadors, at forts limited to the northern half of the 1960 rupture area, wrote of persistent marine inundation near Imperial, Valdivia and Castro that implies widespread tectonic subsidence. They also described a devastating tsunami near Valdivia (Supplementary Table S1, record 1). The 1737 earthquake, known only from secondary sources, damaged the few Spanish settlements then remaining south of Concepción. It lacks a reported tsunami, even though tsunamis from central Chile in 1730 and 1751 were noted locally[14] and in Japan[13,15]. The 1837 earthquake damaged towns along the central third of the 1960 rupture area and changed land levels along the southern half of that area. Its associated tsunami, by reportedly cresting 6 m high in Hawaii[12], provides evidence that the 1837 earthquake released almost half the seismic moment of the

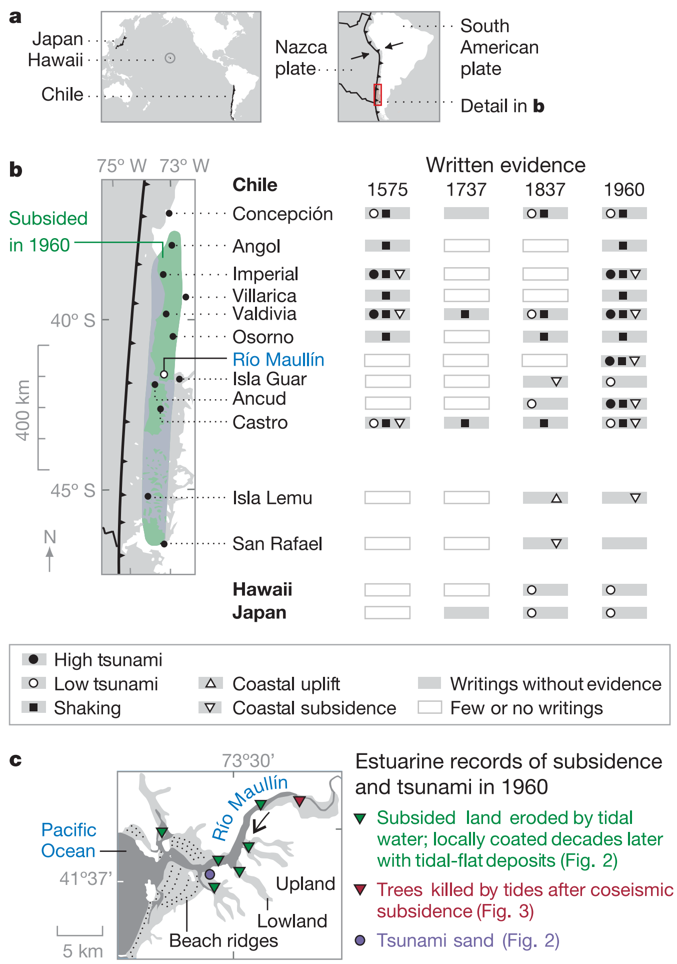


**Figure 1 | Index maps. a**, Plate-tectonic setting of south-central Chile. Paired arrows indicate plate convergence at 8.4 cm yr$^{-1}$. **b**, Documented effects of the 1960 earthquake and its historical predecessors. Compiled from refs 4, 5, 13 and 14, and from Supplementary Table S1. **c**, Study area along the Río Maullín. Barbed lines in **a** and **b** show seaward edges of subduction zones; teeth point down the plate boundary.

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1960 mainshock[16]. However, according to primary sources in Supplementary Table S1, the same tsunami caused little if any flooding at Valdivia and no reported damage anywhere in Chile or Ancud.

To further compare the 1960 earthquake with these historical earthquakes, and to gain perspective from earlier earthquakes as well, we reconstructed a 2,000-yr history of repeated subsidence and tsunamis at the Río Maullín estuary (Fig. 1b, c). Because of the estuary's central location, this history probably includes earthquakes from full-length breaks of the 1960 rupture area, while perhaps excluding earthquakes from partial ruptures to the north or south.

Our stratigraphic records are tied to modern analogues from 1960 along a nearly marine reach of the Río Maullín. There, 8 km inland from the sea (Fig. 1c, purple dot), markers of the 1960 earthquake extend across faint terraces and beach ridges stranded by net late Holocene emergence[17]. Eyewitnesses recall that the 1960 tsunami coated upper terraces with sand[18]. We traced the sand, up to 15 cm thick, more than 1 km inland across the buried 1960 soil in areas covered only by the highest post-earthquake tides (Figs 2a, b). In this same area, the sandy record of post-1960 storms extends just a few metres inland from the shore. On lower terraces, now covered routinely by tides, a 1960 pasture soil has been eroded and bioturbated on post-earthquake tidal flats. Waves and currents are now

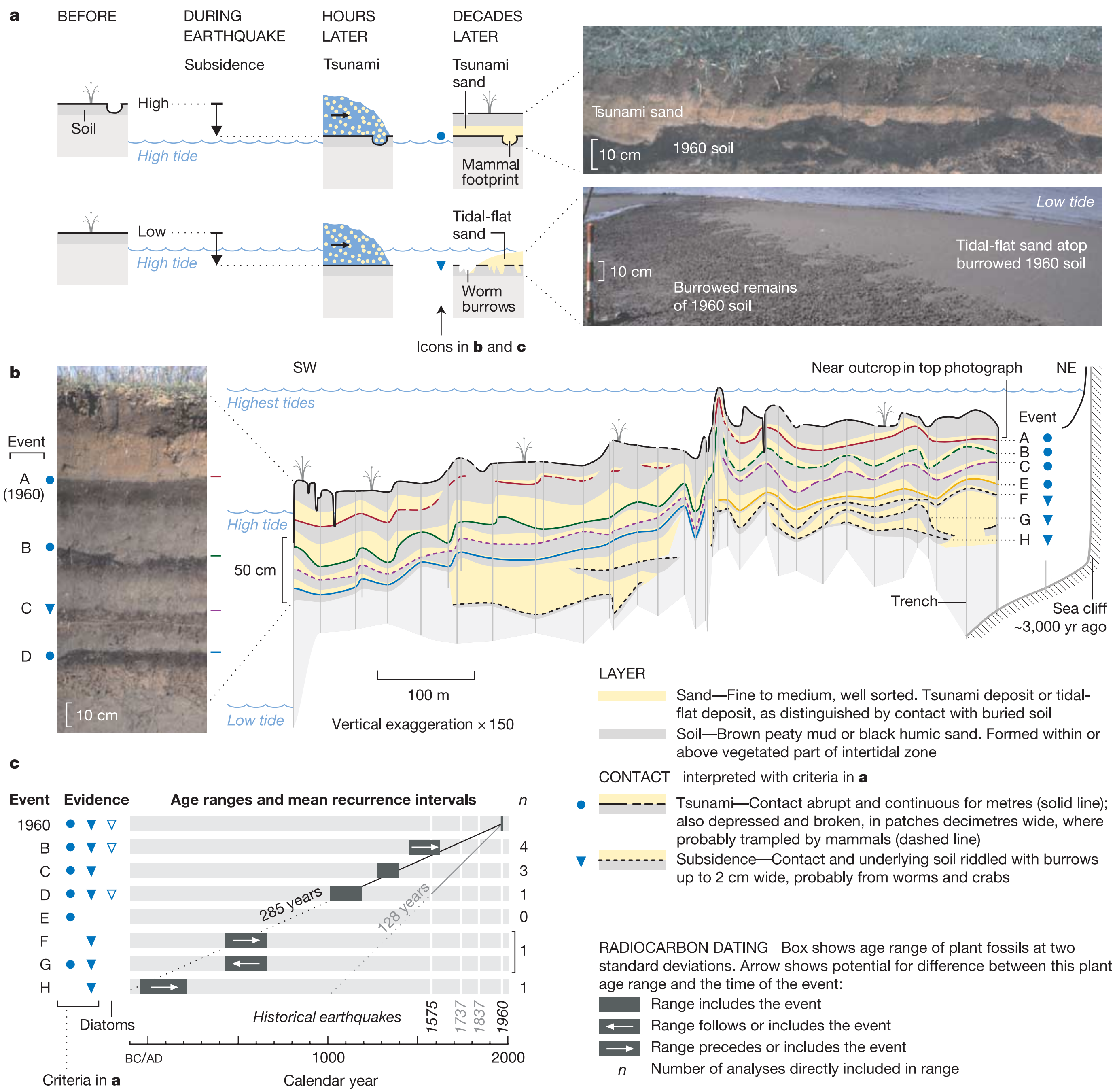


**Figure 2 | Stratigraphic evidence for 1960 earthquake and its ancestors in area shown by purple dot in Fig. 1c.** Supporting data in Supplementary Figs S1–S4 and Supplementary Tables S2–S4. **a**, Records of the 1960 earthquake that serve as modern analogues for inferring past occurrence of a tsunami and of coseismic subsidence. **b**, Sequences of such records correlated among trenches. Tides measured 1989, 2003, and 2004. **c**, Chronology of the inferred events compared with the historical sequence in Fig. 1b. Field evidence for subsidence and tsunami (solid blue circles and triangles at left) comes from all transects (Supplementary Figs S2 and S3). The average of the historical recurrence intervals, 128 yr, contrasts with the longer average intervals between the events recorded stratigraphically.

burying the remains of this soil with sand as much as 1 m thick (Fig. 2a), and with mud in sheltered areas.

Additional sand sheets mantle buried marsh and meadow soils beneath the 1960 soil. Using criteria from the 1960 examples, we interpret some of these sand sheets as tsunami deposits (blue dots in Fig. 2) and others as indicators of subsided, post-earthquake tidal flats (blue triangles). We traced these event records, which probably represent eight earthquakes in all (events A–H), among 60 trenches scattered along 2 km of transects (example, Fig. 2b). Like the 1960 earthquake (event A), four earlier events (B–D, G) produced tsunami deposits on meadows that post-earthquake tides rarely reached and correlative tidal-flat deposits on lower ground. Such evidence, assembled from all transects, is summarized by solid blue symbols in Fig. 2c. Some events are recorded less widely than the 1960 earthquake. The D sand sheet tapers landward without crossing a former beach ridge. The E sand sheet, found entirely inland from that ridge, may have been removed by erosion on the seaward side.

Diatom assemblages from soils that shortly predate and postdate tsunami deposition provide further evidence for subsidence during events A, B and D. In all three cases the assemblages above the tsunami sand are more nearly marine than those in the soil below (summary, Fig. 2c). The difference is clearest for the 1960 event. An attempted comparison for event C failed because the upper part of the buried soil is probably missing from erosion on a post-C tidal flat, and because the remnant soil is contaminated with burrow-filling tidal-flat sand.

In sum, our stratigraphy and paleoecology provide evidence for seven inferred pre-1960 earthquakes from the past 2,000 years (Fig. 2c). The youngest three (B–D), each marked by evidence for both subsidence and tsunami, occurred within the past 1,000 years. Event D dates to the two-sigma range AD 1020–1180—the age of growth-position stem bases of a rush (*Juncus procerus*) that tsunami sand surrounded. The event C tsunami similarly left sand around *Juncus balticus* and *Scirpus americanus* culms in a swale along a spur transect (Supplementary Fig. S3b); below-ground stems (rhizomes) that probably belonged to such plants yielded three statistically indistinguishable ages pooled as AD 1280–1390.

The tsunami deposit from event B probably exceeds the one from 1960 in thickness and landward extent. Because the 1837 tsunami was large in Hawaii[12,16], we expected this penultimate sand sheet to date from the early nineteenth century. Instead, a burned horizon mostly 2 cm below the sand dates to AD 1450–1510 or 1590–1620, as judged from four statistically equivalent ages on charred twigs. Because it followed the fire, probably by a century at most, we correlate event B with the extensive subsidence and devastating tsunami of 1575 (Fig. 1b).

We checked additional estuarine records in a further, futile search for signs of the 1837 earthquake. These records include trees that the 1960 earthquake lowered into tidal freshwater farther up the Río Maullín (red triangle, Fig. 1c). Residents on hand for the 1960 earthquake testify that a forest, green and emergent before the earthquake, lost its foliage from routine tidal submergence in the first few years thereafter. Several decades later, defoliated trunks dominated an area of 10 km$^2$. But several decades after the 1837 earthquake, a nautical chart[19] depicted all trees in this area as leafy (Fig. 3a). In an accompanying report[20], the expedition botanist does not mention dead or dying trees among the forest's riparian plants and animals, which he studied for four days. We cut slabs of 15 dead standing trees in 2003 to estimate their lifespans by counting annual rings. We assume these trees died in 1960. In that case, ten of them were alive in 1837 and two in 1737 (Fig. 3b). This finding suggests that the forest failed to subside in 1837 as much as it did in 1960, in agreement with the nautical survey and the botanist's report.

Shoreline changes provide additional evidence that the 1837 earthquake did not produce 1960-size subsidence along the Río Maullín. Some of the islands and pastures that subsided in 1960 into the middle or lower part of the intertidal zone are barren intertidal or subtidal flats (Fig. 1c, green triangles). At a similar time after the 1837 earthquake, these areas were charted[19] as emergent and vegetated (Supplementary Fig. S1b).

Earthquakes evident in these various estuarine records thus recurred less often than did earthquakes in the historical sequence: 1575, 1737, 1837, 1960 (Fig. 2c). The best-defined of the earthquake intervals recorded geologically, which together span most of the past millenium, average nearly 300 yr—more than double the historical average of 128 years. The 1960 earthquake ended a 385-year interval that includes the years 1737 and 1837. The poorly understood earthquakes of 1737 and 1837 probably released too little seismic moment midway along the 1960 rupture to leave tsunami deposits or subsidence stratigraphy at the Río Maullín.

Where size varies markedly among successive earthquakes on the same part of a fault, much of the fault slip during the largest earthquakes may have thus accumulated before earlier earthquakes of smaller size. Such storage through multiple recurrence intervals probably helps to explain the enormity of the 2004 Sumatra–Andaman earthquake. The fault slip in 2004 near the Nicobar Islands amounted to 10 m (ref. 21) in an area where the fault had last ruptured in 1881 during an earthquake of estimated magnitude 7.9 (ref. 22). By contrast, the fault loading between 1881 and 2004 amounted to less than 4 m at plate-convergence rates recently estimated from satellite geodesy[22] and less than 7 m at rates inferred from long-term plate motions[3]. As in the 1960 Chilean case, the 2004 earthquake may thus have used accumulated plate motion that a previous earthquake left unspent.

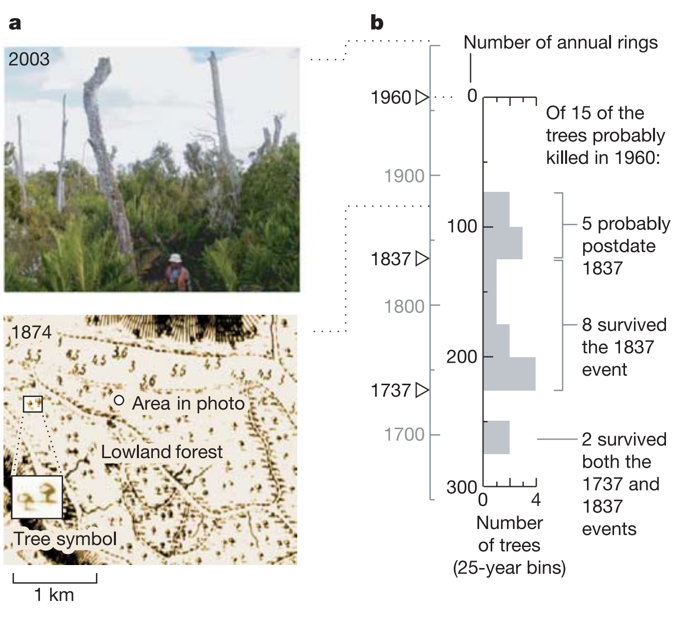


**Figure 3 | Arboreal evidence for difference between the 1960 and 1837 earthquakes, in area shown by red triangle in Fig. 1c.** (See Supplementary Fig. S1d, e). **a**, Views of riparian forest several decades after each earthquake (1874 image from ref. 19). **b**, Counts of annual rings in trees probably killed in 1960 (species, Supplementary Table S4).

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**Supplementary Information** is linked to the online version of the paper at www.nature.com/nature.

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